Enhanced Passive Thermal Propulsion System

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Contract Number: N00014-08-C-0455
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LONG-TERM GOALS

The long term goal is to advance our understanding of thermal energy extraction from the ocean thermocline using an enhanced passive thermal propulsion system. Integration of this new propulsion technology in a low drag hydrodynamic shape is expected to yield undersea glider speeds in excess of 3 Knots (5 Knots may be achievable), and persistence measured in years.

Higher speeds will allow:

- Enhanced glider operations in currents
- Increased measurement rate of ocean parameters of interest
- Reduced timelines to assess parameters of interest in a fixed ocean region

Longer Persistence will provide:

- Potential for underwater glider prepositioning with the ability to “loiter” while waiting for missions
- Reduced logistics manning to deploy and recover vehicles
- Increased measurement area per vehicle deployment

Future technology extensions of this effort will provide propulsion capability in weaker ocean thermocline regions. Hybrid vehicle designs consisting of passive energy extraction and on-board stored energy will likely result, which will increase overall mission flexibility and performance in all oceans.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Enhanced Passive Thermal Propulsion System**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Tusaire Incorporated,11110 Industrial Circle (Suite C),Elk River,MN,55330**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

The comprehensive objective of this effort is to develop an underwater vehicle that consists of an enhanced thermal propulsion system encased in a low drag hull shape that is capable of harnessing ocean thermal energy to propel the vehicle to speeds approaching 3 Knots.

The specific objectives are:

- Research and Development of an enhanced thermal propulsion system including:
    - Development of an engine including variable ballast for propulsion
    - Sizing of heat exchangers
    - Investigations pertaining to engine cycle time reduction
- Low drag hull shape:
    - Leverage Navy and DARPA high speed low drag vehicle design methodologies (TAPS Reference 1) and apply them to the current vehicle hydrodynamic design.
    - Utilize State-of-the-Art CFD tools (FLUENT Reference 2) to support and extend the TAPS methodologies to develop a robust design that will meet the drag requirements associated with 3 Knot speed performance.
- Low Cost Hydrodynamic Structure and Low drag Geometry Shape

APPROACH

Tusaire Incorporated is leading this current research and development technology effort related to the enhanced passive thermal propulsion system. The major subsystems consist of the vehicle hydro shell, which is shaped to satisfy the drag requirement and provide structural integrity over the operational depth regime; primary heat exchanger for extracting energy from the high temperature portion of the thermocline; a return mechanism that resets the propulsion cycle; a thermal propulsion engine; and system engineering, to insure a balanced design.

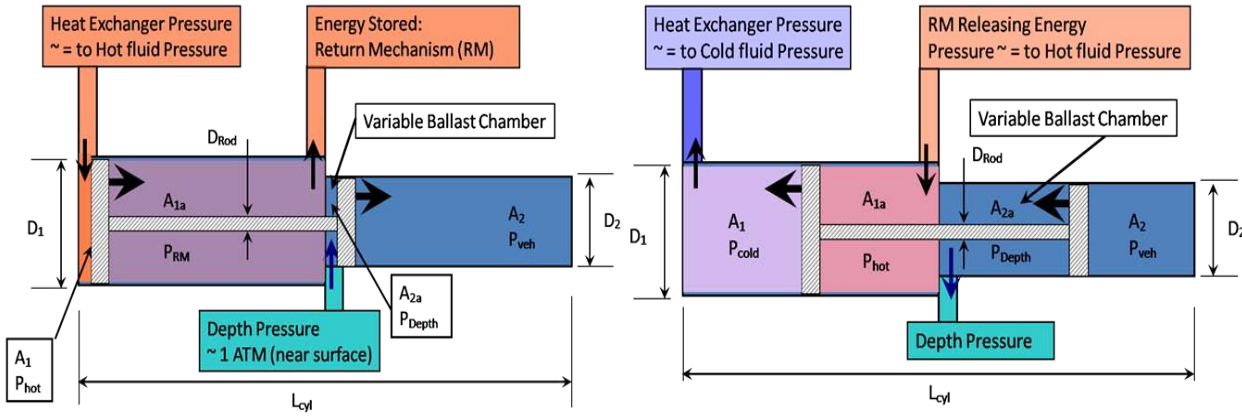
Thermal Propulsion Review:

Details of our FY 2008 effort were provided in Reference 1. Below we provide a very brief summary of the thermal engine prior to discussing the FY 2009 effort.

Thermal Propulsion:

The engine concept for surface and deep operations is depicted in Figure 1 (Reference 3). On the surface heat is transferred from the ocean to the working fluid (WF) in the coil, which drives the engine piston from left to right, this stores pressure-volume (PV) energy into a second WF contained in the return mechanism (RM), and floods the variable ballast chamber (VB) chamber with water

providing downward thrust. At depth PV energy is released from the RM, driving the engine piston from right to left, resetting the engine and purging the VB chamber water. This cycle provides upward thrust.



a) Engine Cycle on the Surface b) Engine Cycle at Depth

Figure 1. Sketch of engine operation at the surface and at depth.

CHALLENGES

The following list contains our FY 2009 challenges. Some of these were known going into 2009 and some developed during the course of the R&D effort.

- Low Cost Pressure and Hydrodynamic Hull
- Acceptable Engine Cycle Time (Surface and Depth)
- Wing design for flight

In 2008 we had developed a hydrodynamic low drag shape design that would serve as hull structure and provide laminar flow at these low Reynolds Numbers. The requirements for laminar flow consist of a proper shape, fabrication of the hull to surface roughness and waviness requirements, and the placing of hull joints as far aft as possible from the nose, in order to avoid boundary-layer flow disturbances. This last requirement, related to the joint placement, is what was driving the fabrication costs. These requirements did not agree well with a low cost hull fabrication. This forced a redesign of the hydro structure which will be discussed in the Hydro structure section under Work Performed. We had initial engine cycle times of > 20 minutes for the surfaced depth cycles (laboratory generated) in FY 2008. We had several discussions with the Navy PO and others and set a goal of 10 min for surface, and < 5 min at depth. Our effort in this area will be discussed in the Engine Cycle Time section under Work Performed.

WORK COMPLETED

The work completed is summarized in these three categories:

1. Hydro Structure
2. Engine Cycle Time
3. ONR Conference Support

Hydro Structure:

High hull fabrication cost quotes drove us to review fabrication approaches and to review historical hull shapes in order to find a lower cost alternative. In a review of historical vehicle fabrication for low cost and expediancy we ran across a WWII Japanese concept related to Kaiten 1 mini-sub (Reference 4). A picture of this vehicle is shown below in Figure 2.

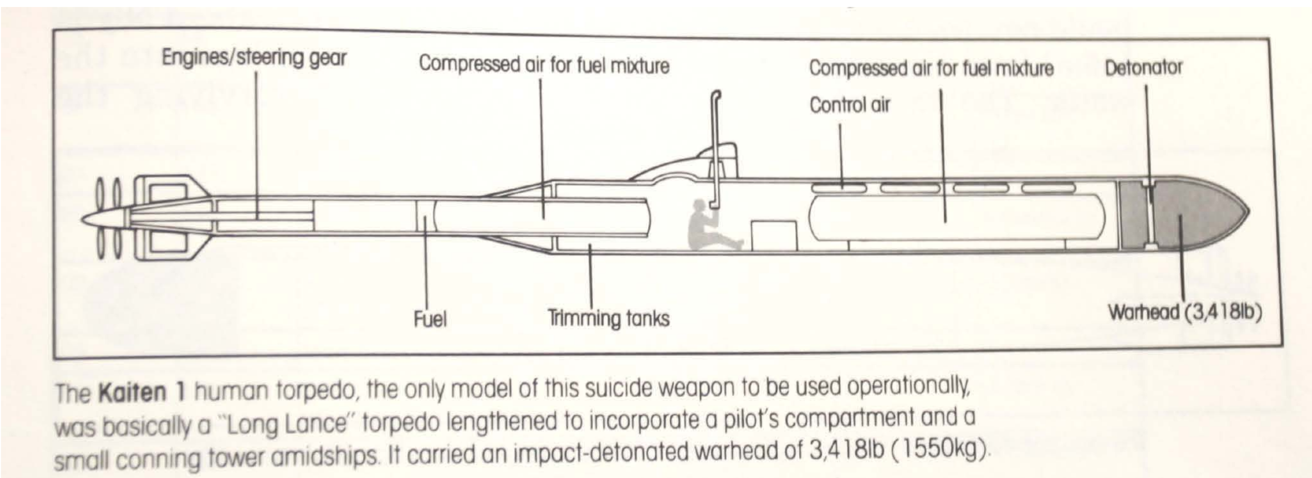


Figure 2. Historical vehicle shape from WWII Japanese Navy (Reference 4).

This concept intrigued us and we investigated approaches built around this idea. This configuration is basically a "dual diameter" shape. We investigated dual diameter shapes including all those shown below in Figure 3.

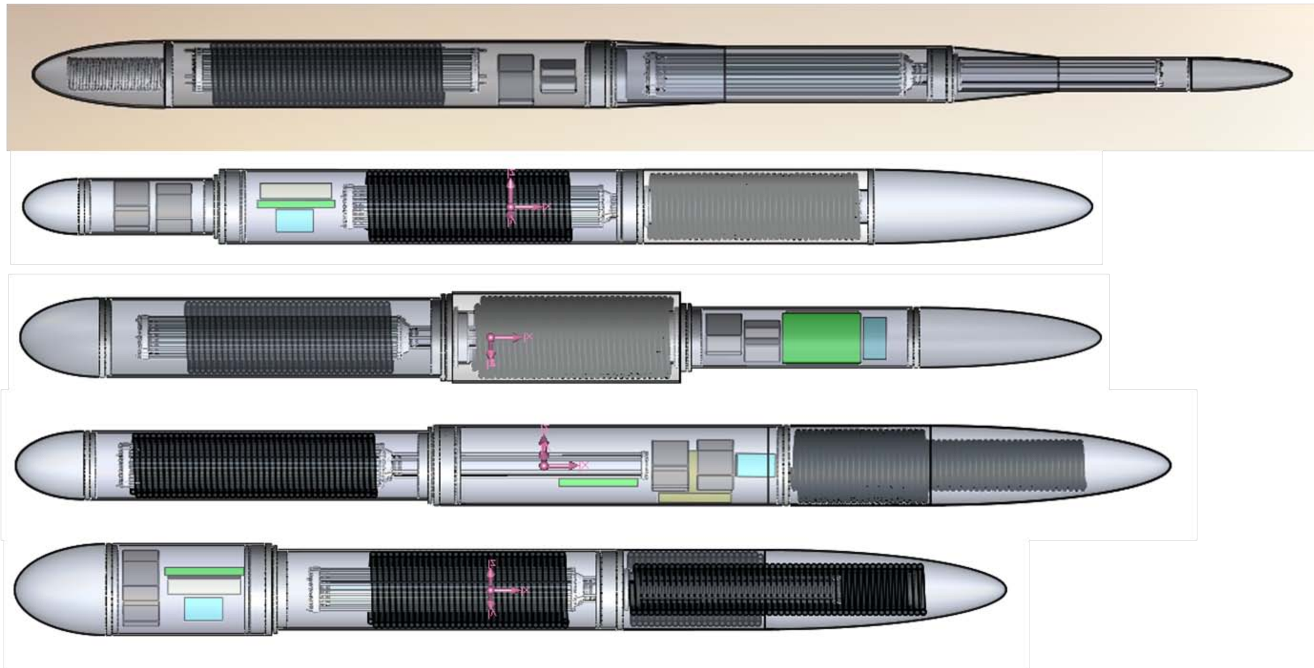


Figure 3. Dual diameter configurations and layouts.

As shown these configurations range from diameters of 7 inches to 12.75 inches and lengths of 10 feet to 15 feet. Each of these configurations have substaintially lower fabrication costs than the previous low drag shape. However speed predictions for these shapes were below the goal of 3 Knots, and the propulsion team was pushing heat exchanger temperature preconditioning using free flooded fairings in order to reduce the cycle time. This led us to a pressure hull design using free flooded fairings. This design satisfies the speed requirement and provides flexability for the return mechanism preconditioning. The design is shown in Figure 4, and the fabricated hardware is shown in Figure 5 and 6.

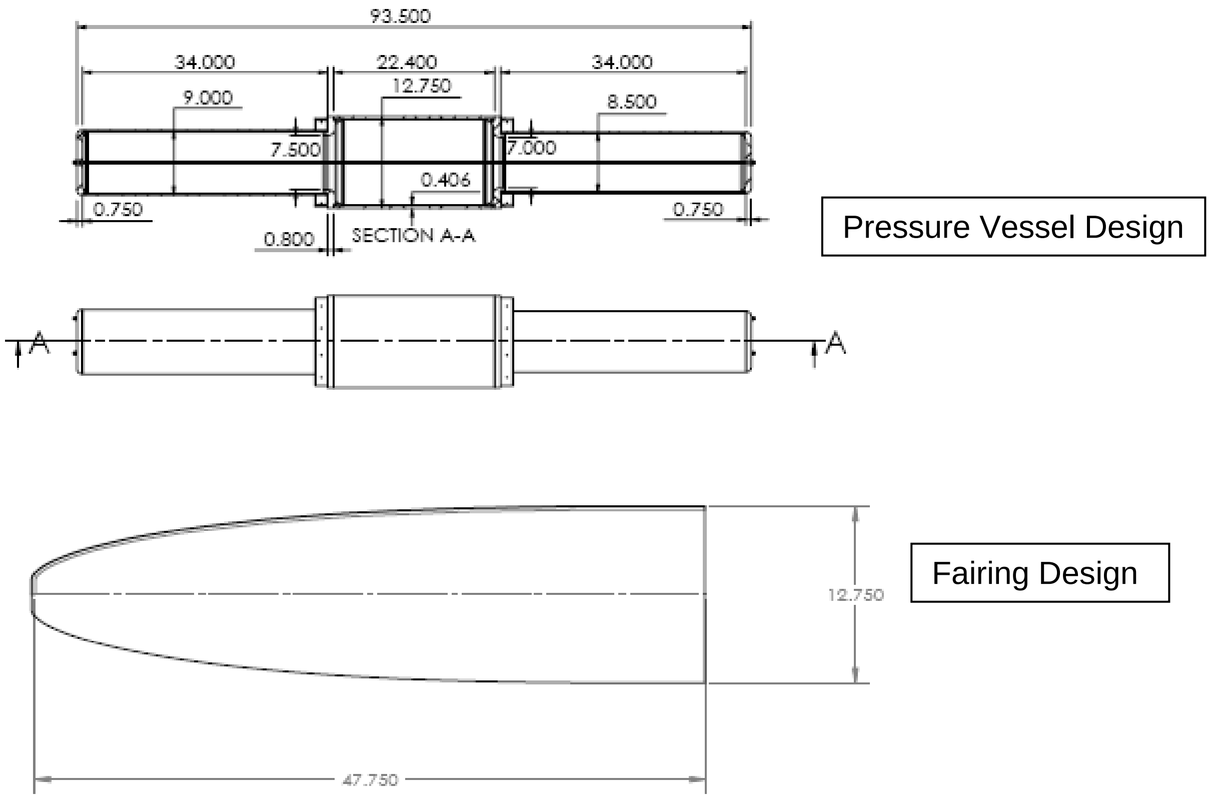


Figure 4. Pressure vessel, and fairing design (dimension units are in inches).

Figure 5. Fabricated pressure vessel.

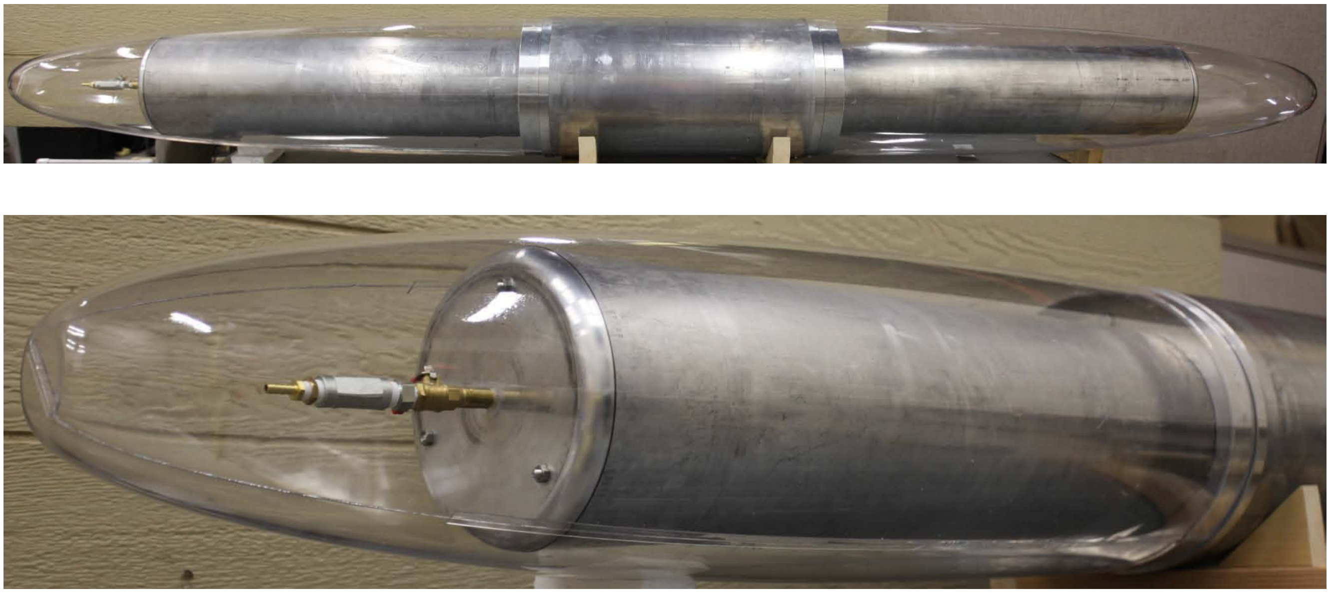


Figure 6. Photo of fabricated fairing installed onto the pressure vessel.

Hydro Structure Summary:

We have developed, designed, and fabricated a low cost hull consisting of a water tight pressure vessel, with free flooded fairings that are based on laminar flow geometry shapes (for drag reduction). The vehicle size grew from the previous 9 inch diameter shape to 12.75 inches. This growth was a primary result of switching to a pressure vessel design with fairings, heat exchanger size growth (to reduce cycle times), and heavier continuous coils made from stainless steel (continuous coils minimize joints and seal issues). The final vehicle size is 323 mm (12.75”) in diameter, and 3.05 m (10 feet) long.

Time Constants associated with the Thermal Cycle:

A detailed discussion of thermodynamic heat exchanger cycle times and associated non-isothermal issues were presented in the FY 2008 ONR report (Reference 3). During FY 2009 we have worked on reducing these cycle times to reasonable operational values. The time related for energy storage (surface operation) and energy release (depth operation) is a function of non-isothermal behaviors associated with compression and expansion of working fluids. The goal in 2009 was to approach isothermal conditions and to have faster cycle times. Figure 7, contains data associated with theoretical predictions, laboratory data for non-isothermal conditions and laboratory data for near isothermal conditions. The red and purple curves show predictions based on NIST (Reference 5) for isothermal assumptions. Isothermal conditions during the cycle are desired since this will lead to a constant force condition for both energy storage and energy release. The green data trace shows results from testing associated with non isothermal behavior (pressure feedback increases from temperature changes during the cycle). In this case a variable force (increasing with time) results and causes the cycle time to increase. The blue data trace shows results for near isothermal conditions. The force for this trace is nearly constant over the cycle and results in reduced times. Heat exchanger

preconditioning is one way to attain near isothermal conditions, and this can be achieved by using free flooded fairings with surface water surrounding the return mechanism heat exchanger, and depth water surrounding the energy extraction heat exchanger. However this requires an operational fluid exchange on each swim cycle for preconditioning. In order to maintain persistence the energy required for this fluid exchange will need to be very low.

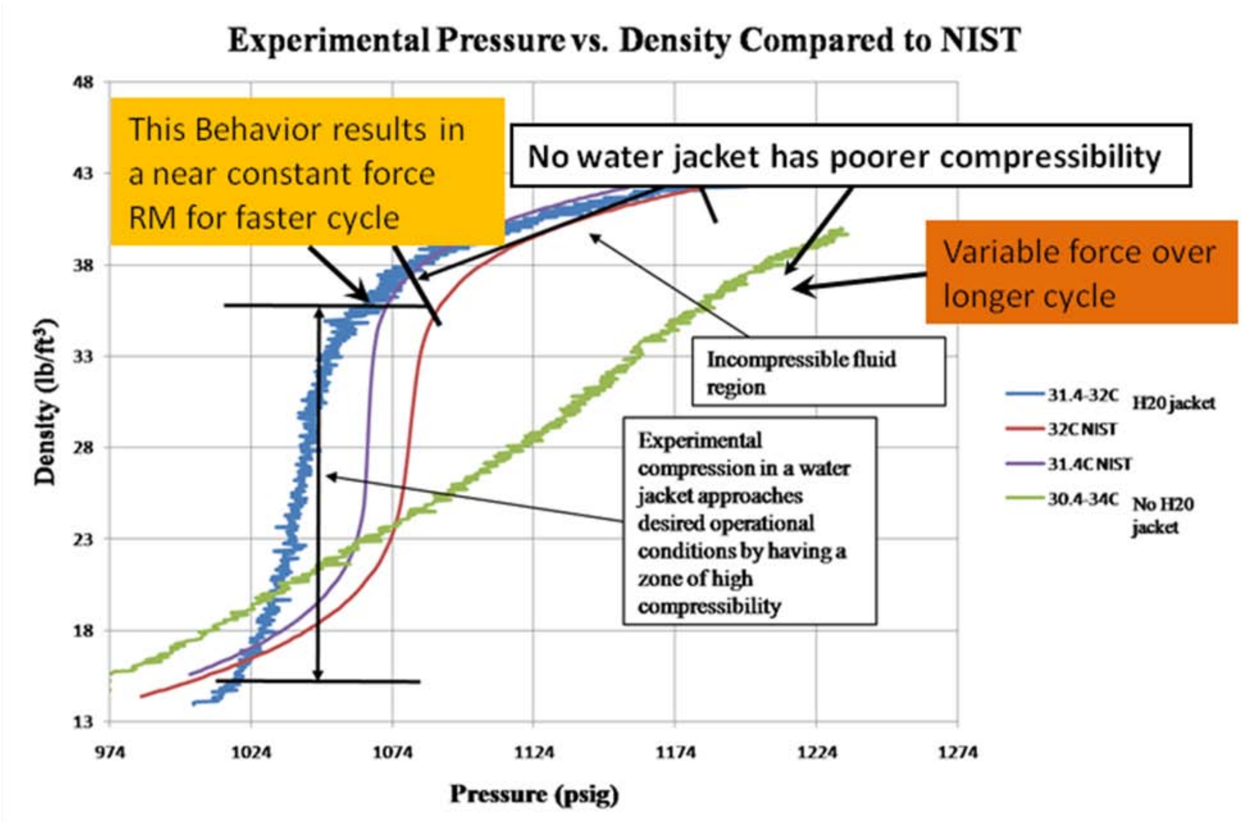


Figure 7. Theory and laboratory data related to isothermal and non-isothermal engine density behaviors.

Laboratory setup and hardware testing photos are shown below in Figure 8. Elements shown consist of the Tusaire Engine, heat exchanger coil, chillers to simulate depth temperatures, ballast exchange of 2 Kg that works against a 330 m (1000 foot) depth pressure via a high quality, high resolution pressure relief valve, and our instrumentation and data acquisition system.

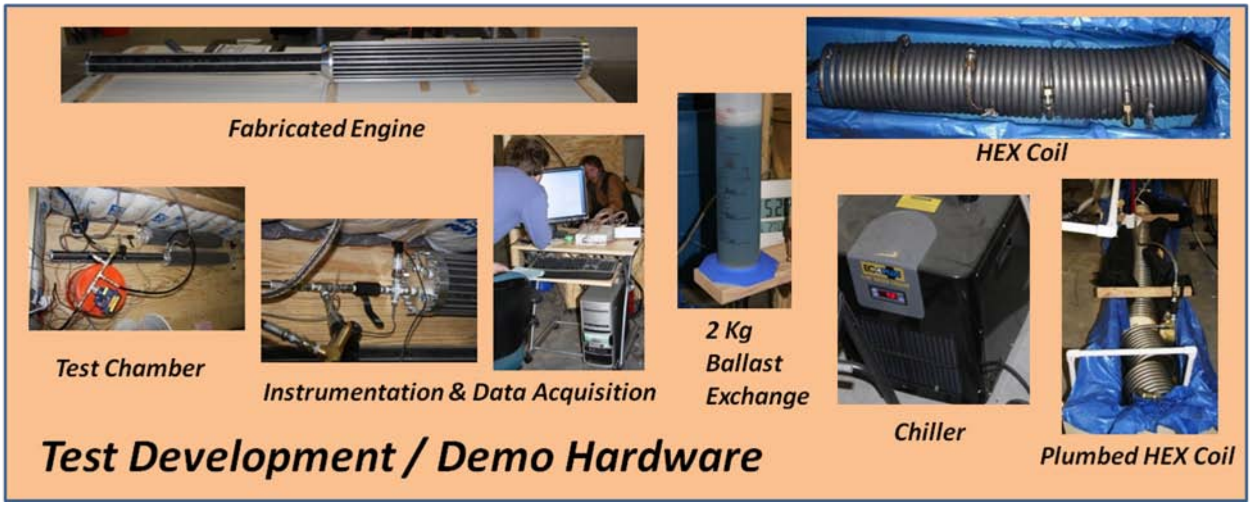


Figure 8. Laboratory setup and test hardware.

During laboratory testing with temperature and pressure matching swim operations Tusaire has demonstrated the ability of our system to purge 2 Kg of ballast at a depth associated with 330 m (1000 feet). The system is designed for a temperature difference between the surface and depth of ~ 15 deg C; however we have performed successful tests for temperature differences as low as ~ 10.5 deg C. We are encouraged by this propulsion system's ability to change its variable ballast by 2 Kg, however we still have challenges maintaining near isothermal behavior for short cycle times, and keeping the power budget very low related to preconditioning.

With preconditioning we have demonstrated surface cycle times associated with storing thermal energy from the ocean of ~ 10 minutes. At depth the time to release this energy to blow the ballast and return to the surface is ~ 3 minutes. Numerous repeat experiments have been performed with similar results. These times are below the values established as goals.

The current vehicle is shown in Figure 6. As a result of this new vehicle and size increase we also performed new hydrodynamic drag predictions and provide those results below under hydrodynamics.

Hydrodynamics of the Resultant Shape:

Our new shape consists of a maximum diameter of 324 mm (12.75 inches), and a length of 3.05 m (10 feet). In our hydrodynamic design effort we found that we could place blunt nose geometries on the fairings and still maintain a very good pressure distribution for use in passive laminar flow stabilization. The blunt nose and tail shapes increase the vehicles prismatic coefficient and provides increased volume for installation of equipment. The nose and tail fairings are identical for operational flexibility and low cost. The hydrodynamic assessment is performed with the TAPS Code and FLUENT (References 1 and 2). The resultant pressure distribution is shown in Figure 9, based on FLUENT predictions.

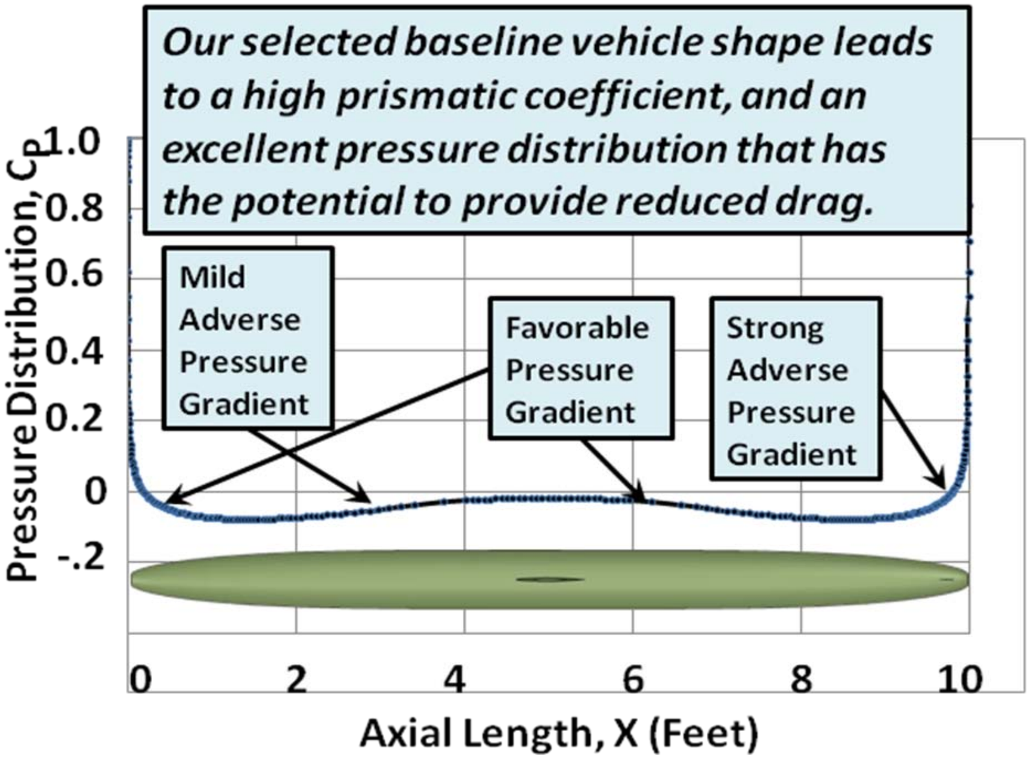


Figure 9. Pressure distribution associated with the new geometry shape.

As shown the Tusaire hydrodynamic shape generates a pressure distribution with very mild adverse pressure gradients. The combination of these mild adverse pressure gradients and operational low Reynolds Numbers provides the possibility for extensive laminar flow (low drag) over the vehicle which will be discussed next.

Detailed analysis of boundary-layer flow was performed using the TAPS code. Boundary-Layer stability predictions from TAPS (using the e^9 shape factor correlation see Reference 6 for more details) are shown in Figure 10 for our previous 9 inch diameter shape and our current 12.75 inch shape.

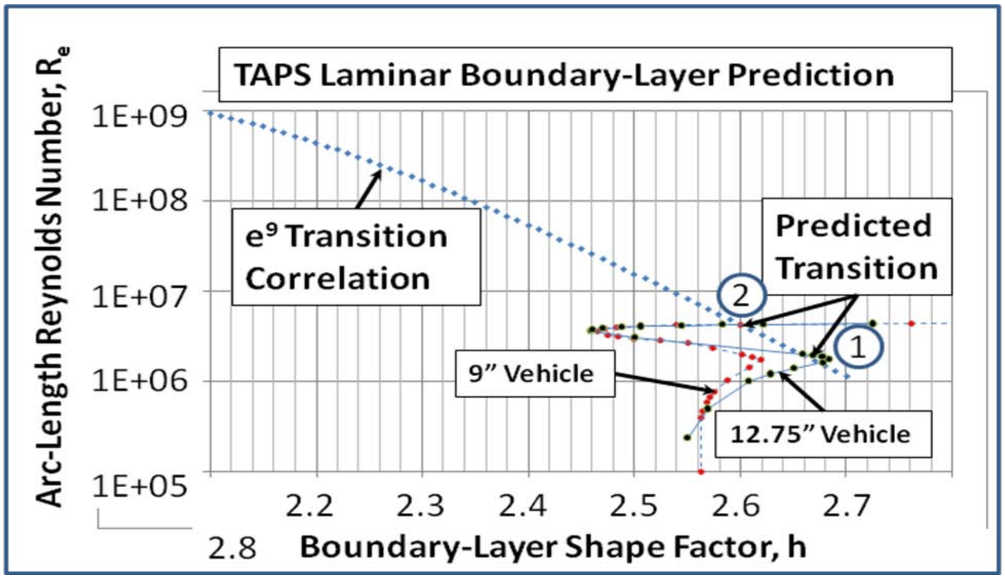


Figure 10. Transition prediction associated with the new geometry.

In this correlation of shape factor and e^9 stability, transition is predicted to occur when the boundary-layer shape factor crosses the e^9 transition correlation. As long as the boundary-layer shape factor .vs. Reynolds Number curve is below and to the left of the correlation, laminar flow is predicted. Once the shape factor curve crosses the correlation then transition is predicted to occur at the crossing location. As shown the 9 inch diameter configuration crossed at location 2, and the 12.75 inch vehicle shape has two crossings, number 1 and 2. The drag associated with these two crossings for our latest 12.75 inch geometry is shown in Figure 11, along with all turbulent flow predictions and transition occurring at minimum pressure.

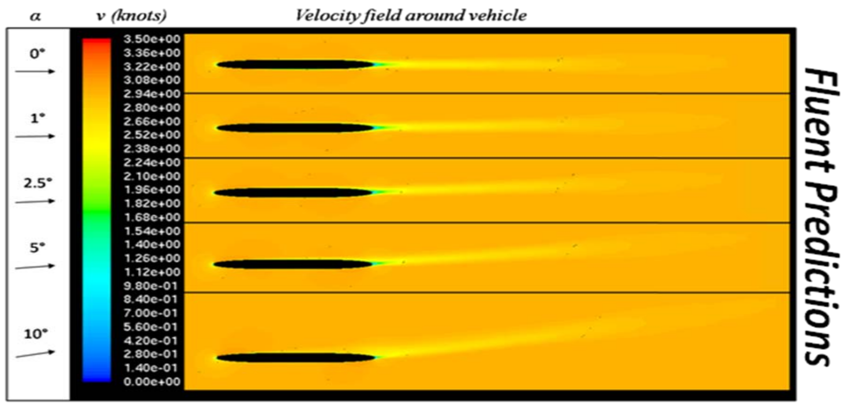
3 Knot Flow Condition	C_D	Drag (Kgf)
All Turbulent with Pressure Drag included from FLUENT	0.12284	1.264
Laminar to Cp-min with Pressure Drag included from FLUENT	0.11553	1.189
Laminar to 1st crossing with Pressure Drag included from FLUENT 1	0.09117	0.9383 **(Expected)**
Laminar to 2nd crossing with 2 Pressure Drag included from FLUENT	0.03355	0.3454 **(Possible)**

Vehicle Drag Predictions show Drag < 1 Kgf

Figure 11. Drag predictions for the new larger sized vehicle.

As shown the drag varies from 0.3454 Kgf for crossing 2, 0.9383 Kgf for crossing 1, 1.189 Kgf for transition at minimum pressure, and 1.264 Kgf for turbulent flow starting at the nose. We believe the results from the crossing 1 location will be achieved and we may have the ability to approach the low drag levels associated with crossing 2. The drag and resultant vehicle speed associated with crossing 1 will approach the goal of 3 knots. The resultant speed will be higher if crossing 2 is achieved.

The last hydrodynamic drag investigation for the new larger geometry relates to drag sensitivity to angle-of-attack variations. A full 3-D analysis was performed in FLUENT and is shown in Figure 12, for angle of attacks varying from 0 to 10 degrees.



Velocity field contours around the vehicle for varying angles-of-attack, α. Flow separation sensitivity to α is minor – and therefore the drag is very stable.

Figure 12. Vehicle hydrodynamic flow sensitivity to angle-of-attack variations.

As shown the flow is very well behaved with no major flow separation regions identified. For angle-of-attacks below 5 degrees drag changes are predicted to be negligible. Hydrodynamic drag predictions for the new larger shape indicate that the 3 knot speed goal is still achievable. However the acceleration time lines to reach 3 knots will be increased for the new larger vehicle as a direct result of vehicle mass increase.

The discussion below relates to ONR's request for Tusaire to investigate underwater flight wing design and flight predictions. This effort was started in late FY 2009 and will continue into FY 2010. A two pronged approach has been started related to underwater flight. The first investigated flight performance using a 6-DOF model and nominal early data for the vehicle and wing, and the second relates to wing sizing. The flight predictions will be presented first with the wing sizing effort presented second.

Preliminary flight investigation

The preliminary flight investigation is based on the vehicle being on the surface and starting a dive with the parameters as stated below:

- Drag for 100% turbulent flow (high drag condition)
- Maximum diameter is 324 mm (12.75 inch)
- Initial pitch angle : -30 degree
- Thrust : 0.2kg , 0.5kg , 1.0kg (three thrust settings)

- Wing position : 0m , 0.01m , 0.02m (three wing positions)
- Position of CG : 0.0m
- Position of tail : -1500mm
- Mass of the vehicle : 200kg (upper limit of mass)
- Overall size of the vehicle : length 3810mm(150inches) (upper limit of length)
- Wing span 1824mm(71.81inches)
- Wing root chord is 250 mm (9.84 inches)
- Wing tip chord is 125 mm (4.92 inches)

Some of these parameters are on the high side since they were established prior to the redesign (discussed previously) being finished. The mass is 42% high and affects acceleration, the vehicle length is 25% high and affects surface area and drag, and the flow was assumed 100% turbulent (high drag flow) which affects the vehicle drag. These parameters account for ~ 43.4% higher body drag than expected for 3 knot flight. The wing size was initially scaled from previous gliders such as sea glider. The wing sizing study shows that scaling the wing designed for a nominal 0.5 knot speed was not the best approach since our design speed is approximately six times higher. This larger scaled wing size then also contributes to more drag than is expected. Based on these higher drag values the 6-DOF speed predictions are lower than what is actually expected. Future work in FY 2010 will refine these parameters and bring the drag in line with what is expected, as well as updating the 6-DOF predictions.

The approach is to first investigate open loop flight characteristics to determine nominal wing placement relative to the CG, then investigate preliminary control methodologies based on CG changes. The coordinate system is shown in Figure 13.

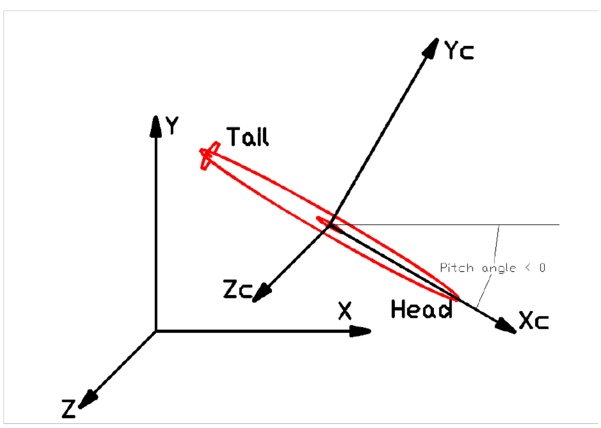


Figure 13. Coordinate system used for 6-DOF simulation.

Preliminary open loop predictions:

Open loop predictions as a function of time for various thrust and wing positions are shown in Figure 14 (A: pitch plane X and Y position), (B: pitch angle), and (C: Pitch Rate). These results indicate that wing positions forward of the CG between 0.01 m and 0.02 m will result in near constant pitch angle flight for open loop conditions.

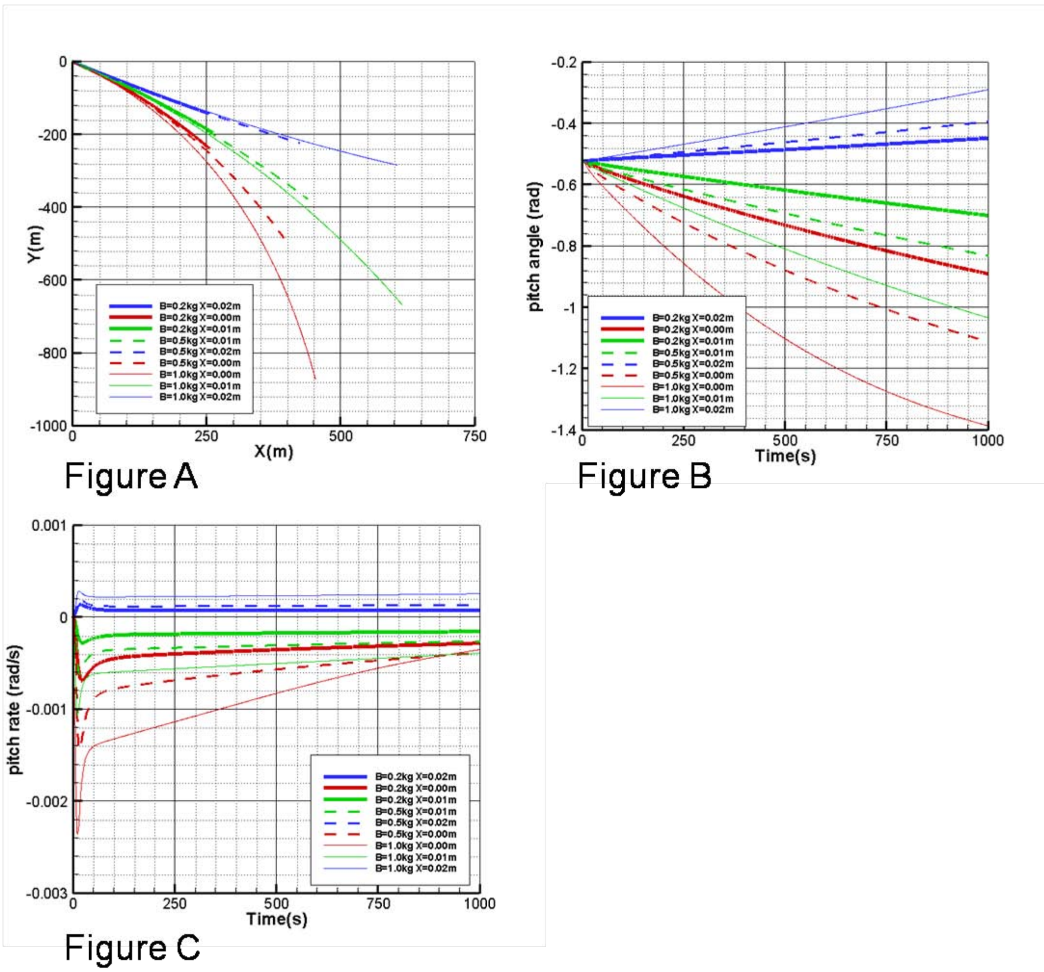


Figure 14. Open loop flight prediction. X-Y position (A), Pitch angle (B), and Pitch Rate (C).

Velocity predictions for open loop flight are presented in Figure 15 for horizontal, vertical, and total. Velocities are predicted to exceed 1 m/sec(~ 2 knots) for the full thrust condition at times of 300 sec and 750 sec for the red and green curves. As stated previously these speeds are lower than what we actually expect.

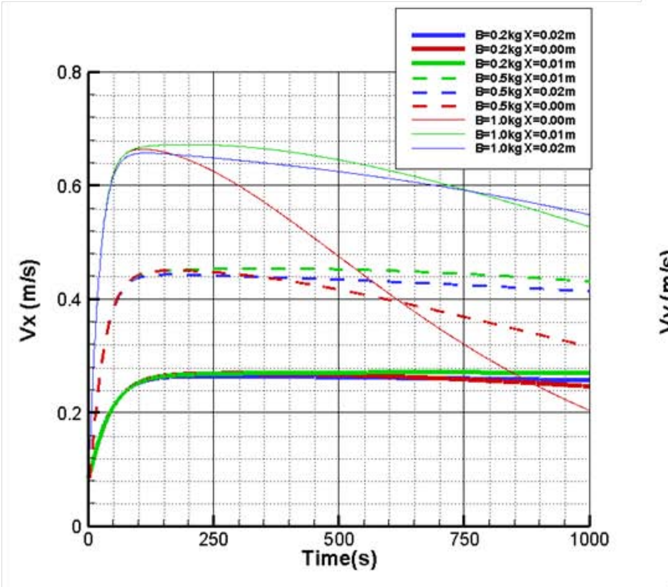


Figure A

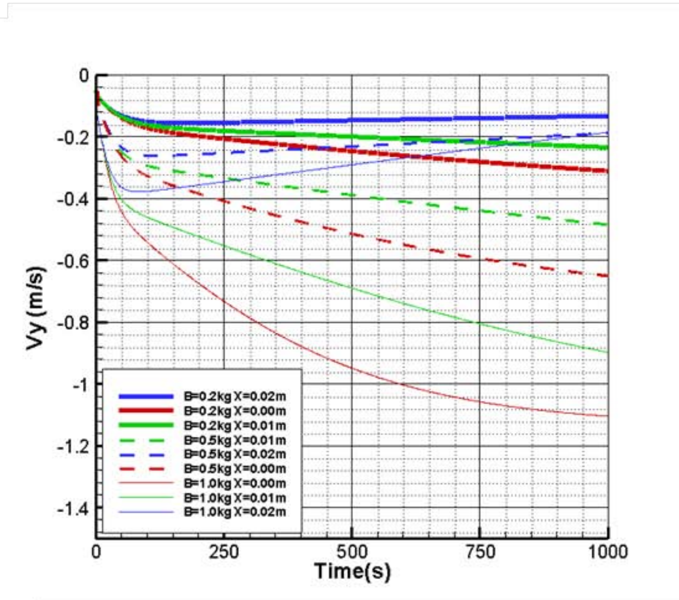


Figure B

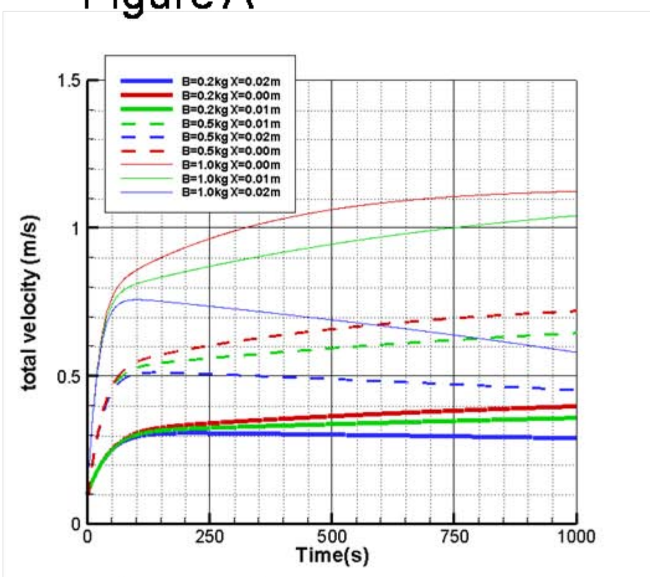


Figure C

Figure 15. Velocity predictions for open loop flight, Horizontal (A), Vertical (B), and Total (C).

Preliminary flight control:

The first method of control that has been investigated is related to CG shift control. Preliminary results are presented in Figure 16 for position, pitch angle, and pitch rate. The velocity predictions are shown in Figure17, and the CG motion requirement for control is presented in Figure 18. The CG control requirements can be satisfied by a 5 Kg mass moving 142 mm.

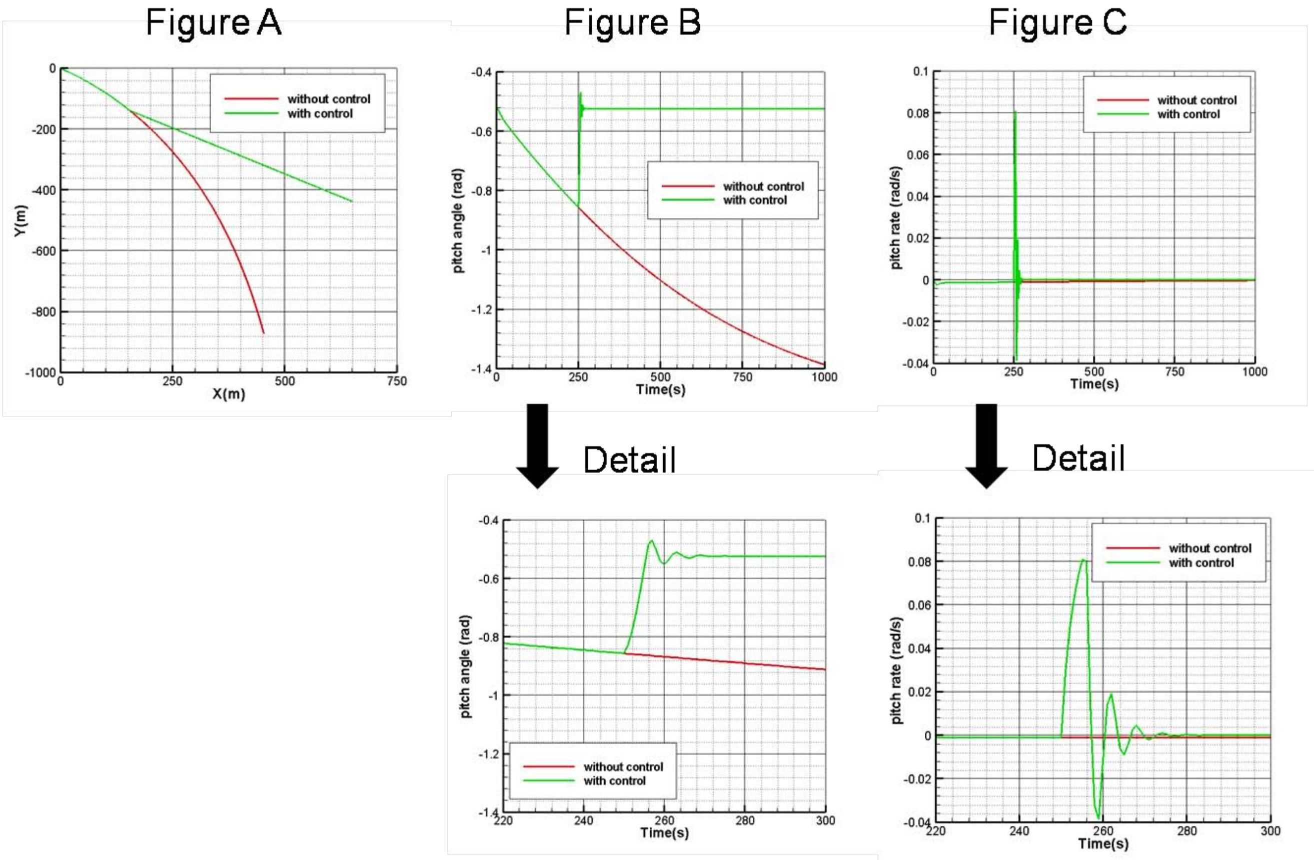


Figure 16. CG shift Control predictions. Position (A), Pitch Angle (B), and Pitch rate (C).

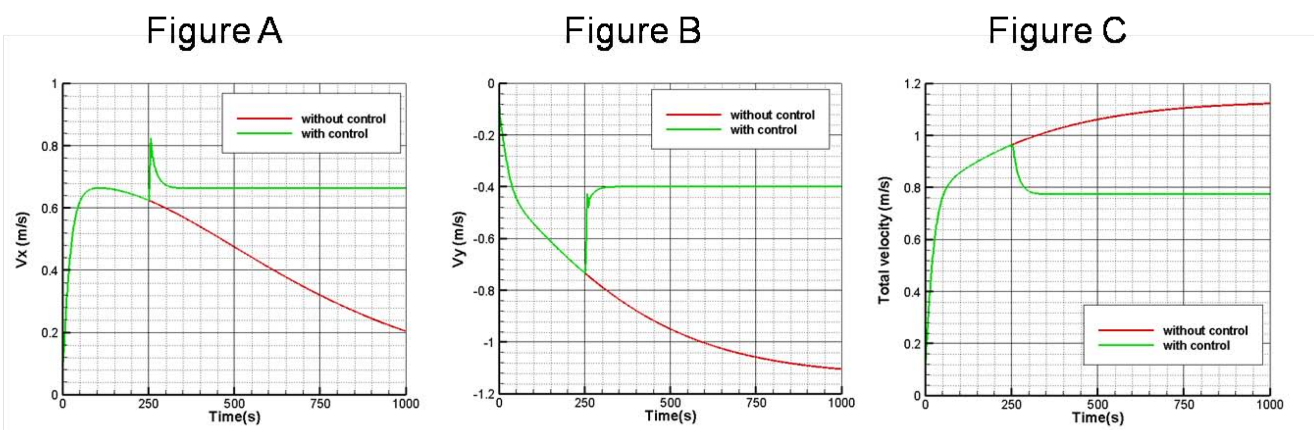


Figure 17. Velocity Predictions for CG shift Control. Horizontal velocity (A), Vertical Velocity (B), and Total Velocity (C).

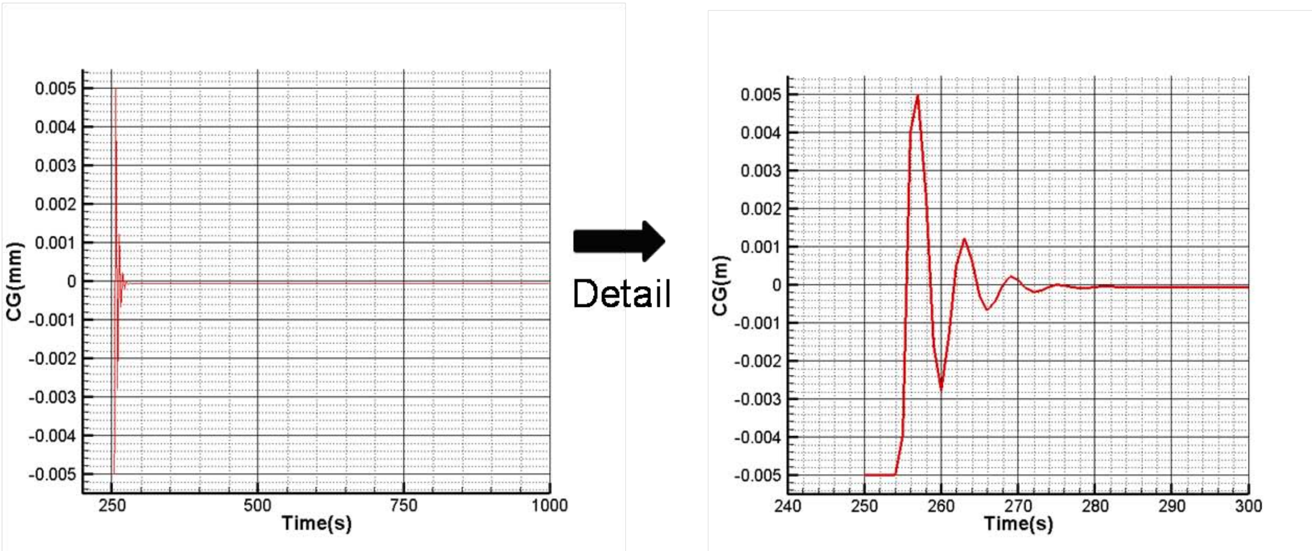


Figure 18. CG control position as a function of time.

The control predictions to date indicate that CG shift control may be a viable form of vehicle control for the parameters assessed. The shifting mass size and power requirements for CG shifting will be determined in FY 2010.

Preliminary wing sizing for flight:

We developed a simple hydro wing sizing model to guide us in the preliminary wing design process. This model is based on wing size, surface area, skin friction drag, lift requirements, lift curve slope, angle of attack and induced drag for maintaining constant glide angle. To assess or calibrate the model's prediction capability we ran it for nominal gliders in the size range of sea glider, with our predictions shown in Figures 19 and 20 for angle-of-attack, mean chord, and wing span.

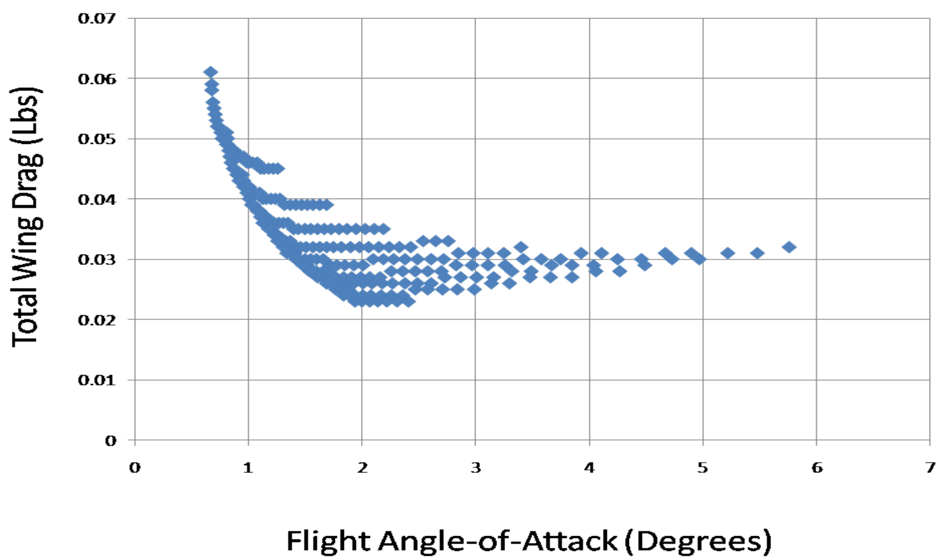


Figure 19. Small glider test case for angle-of-attack and wing drag.

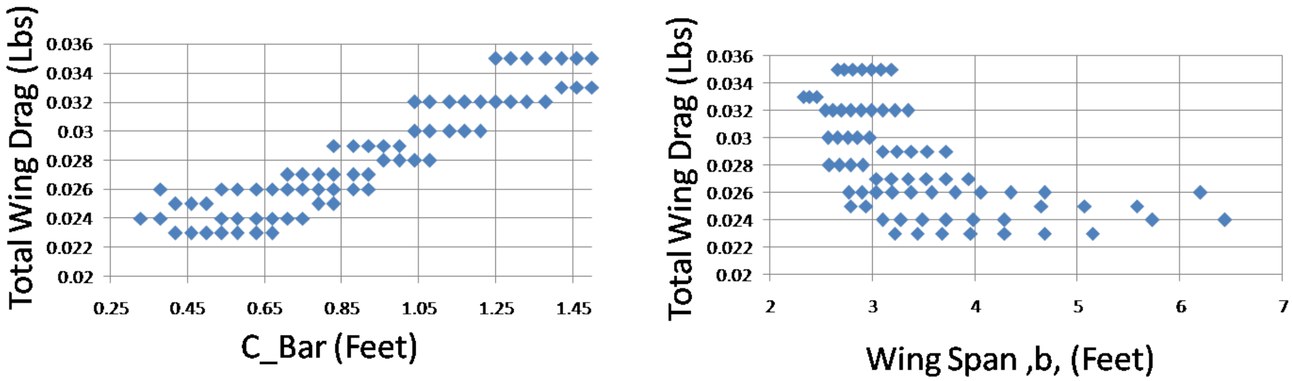


Figure 20. Small glider test case for mean chord, wing span and wing drag.

The minimum drag prediction for the wing occurs at around a 2 degree angle of attack. In Figure 20, the wing mean chord and wing span for an operating angle of attack of around 2 degrees are shown. The mean chord for minimum wing drag is ~ 0.5 feet and the wing span is ~ 4 feet. These values are close to the actual small glider values. This gives us confidence in the prediction tool.

This tool has also been used to generate preliminary wing sizes needed for constant glide slope angle flight for our current vehicle size and shape. Wing drag prediction as a function of aspect ratio is presented in Figure 21. The aspect ratio for low drag ranges from ~ 1.1 to ~ 1.3. The wing span predictions are shown in figure 22, and show best span lengths ranging from 0.8 feet to 1.0 feet. The mean chord predictions are shown in Figure 23 and show that a chord of 0.75 is ~ best. The resultant flight angle-of-attack is presented in Figure 24 and shows recommended angles between ~ 2 to 5 degrees.

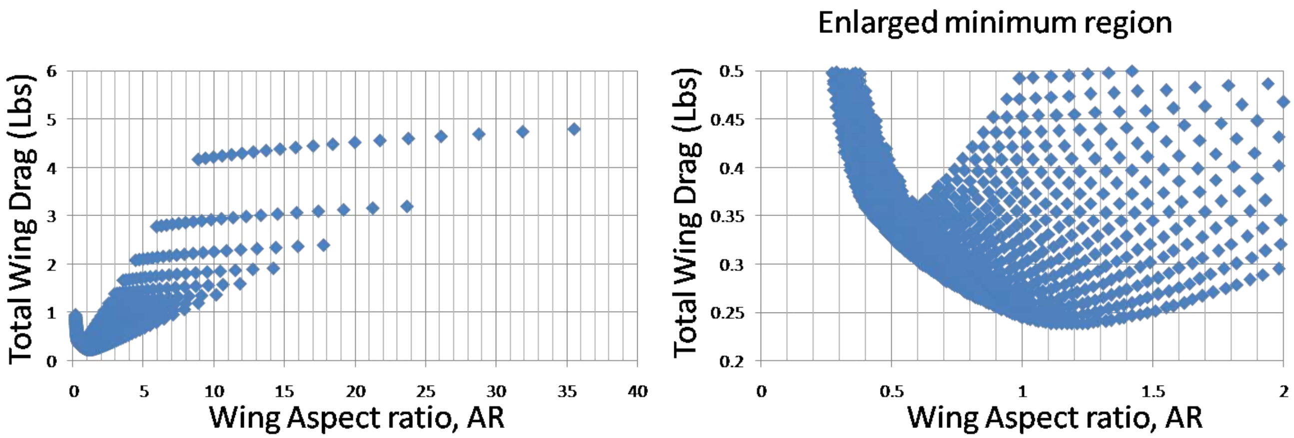


Figure 21. Predicted wing drag as a function of Aspect Ratio.

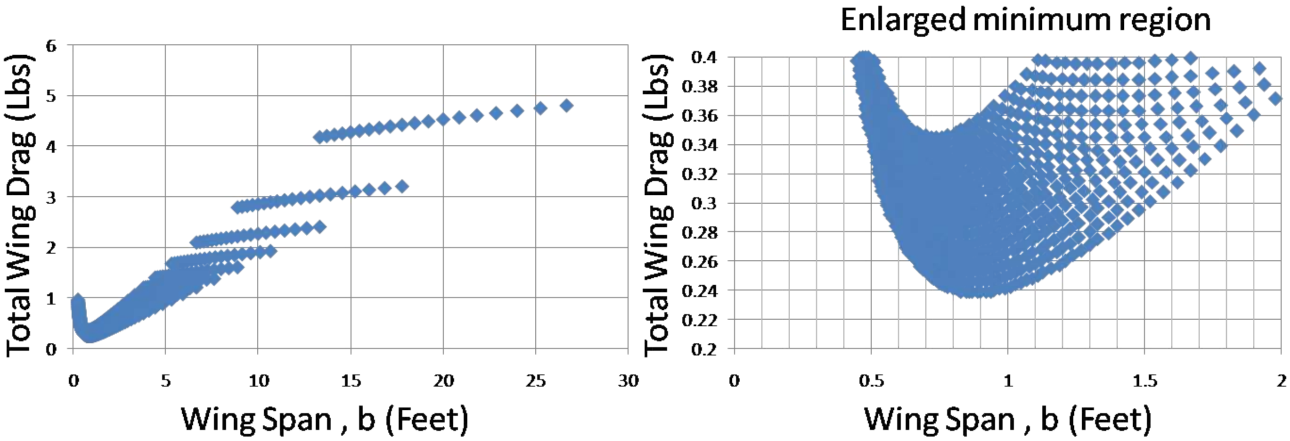


Figure 22. Predicted wing drag as a function of span length, using sizing output data.

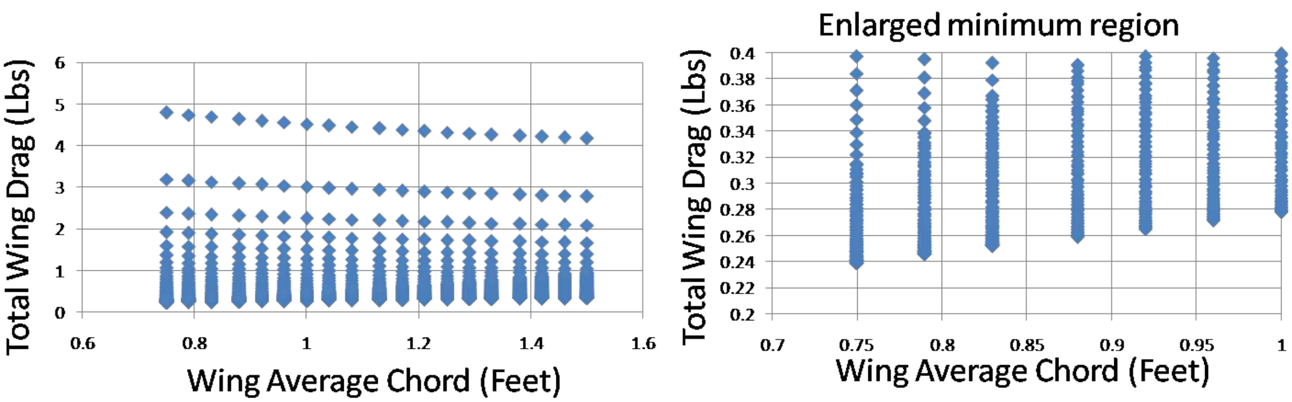


Figure 23. Predicted wing drag as a function of chord size, using sizing output data.

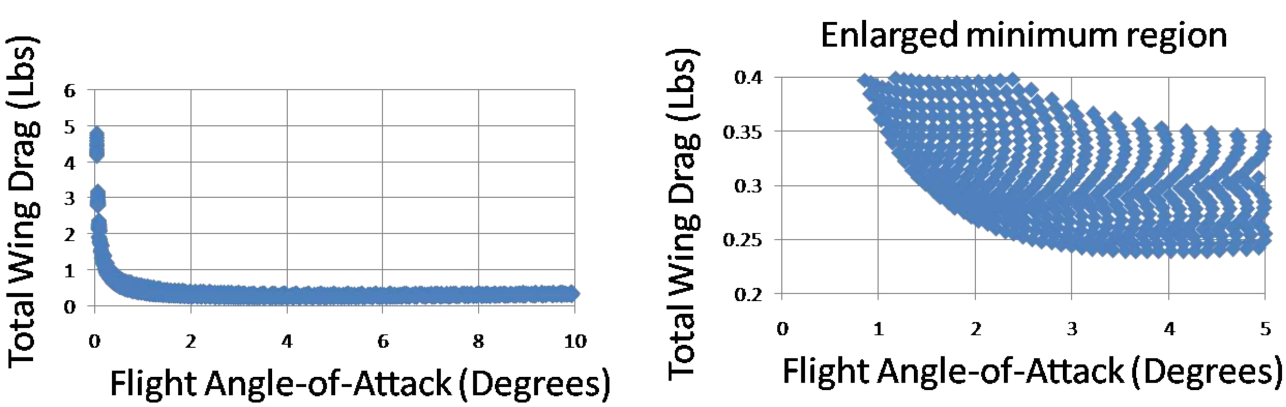


Figure 24. Predicted wing flight angle-of-attack for low drag, from sizing output data.

The preliminary wing size recommendation is substantially smaller than the wing sized used in the 6-DOF study. These sizes will be checked and the 6-DOF predictions updated with the new wing size during our 2010 effort.

RESULTS

Our meaningful technical results achieved in 2009 are:

- Results to date indicate that the goal of attaining 3 Knot speed performance from propulsion based on energy extraction from the thermocline is achievable.
- We have learned that non-isothermal behavior (temperature changes less than 5^o C) can have negative impacts on cycle time constants. We have reduced engine cycle times from ~ 25 minutes to 10 minutes for surface and <~3 minutes at depth.
- The vehicle hydrodynamic hull has been redesigned and fabricated at a substantial lower cost.
- The new vehicle size is larger. Hydrodynamic drag assessments still indicate that speeds approaching 3 knots are feasible.
- Preliminary flight and wing sizing has been started with preliminary results indicating that flight control will be possible for CG shifting control. Shifting weight and power requirements will be assessed in 2010.
- Wing sizing study indicates that lower aspect ratio wings (relative to previous gliders) will provide better performance.

IMPACT/APPLICATIONS

Potential future impact for Science and/or Systems Applications is the substantial increase in underwater glider speeds and persistence. Current thermal gliders operate in speeds measured in a few tenths of Knots. This enhanced thermal propulsion technology has the potential to provide speeds approaching 5 Knots in the future.

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